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Foliage temperature, screen temperature and the calculation of long wave radiation from the surface

by N. Thompson

1. Introduction The calculation of actual or potential evaporation from a crop requires estimates of available energy (the difference between downward net radiation at the crop surface and downward soil heat flux). There are many published schemes for evaluating the net radiation. On a daily basis the short wave contribution may be estimated satisfactorily using a relation of the basic form

$$R_s(net) = R_a(1-\alpha_s)(a + b\,n/N) \qquad (1)$$

where

R_a = daily shortwave radiation from a transparent sky
α_s = short wave albedo
a, b = constants which vary with location and season
n = measured duration of bright sunshine
N = maximum possible duration of bright sunshine at the site.

The long wave contribution also can be estimated in a variety of ways. A convenient method is to use Swinbank's (1963) empirical relationship for the downward component, and to calculate the upward component by Stefan's law, leading to a net flux

$$R_L(net) = (1-\alpha_L)(\sigma(1.03T_{scR}^4 - T_s^4) - 113)(0.1 + 0.9\,n/N) \qquad (2)$$

where

α_L = long wave albedo
σ = 5.67×10^{-8} $Wm^{-2}(\text{deg K})^{-4}$
$T_{scR} = T_a + 273.15$ = screen temperature in deg K
T_s = surface temperature in deg K

The difference between screen and surface temperature varies quite widely with available energy, wind speed, vapour pressure deficit, surface roughness and soil moisture deficit. The remainder of this Memorandum explores the derivation of empirical relations between screen and surface temperature which take some or all of these factors into consideration.

2. Theory The basis of a suitable treatment has been outlined by Thompson (1978). The required relations are the usual representations of the diabatic temperature profile, for unstable conditions

$$\begin{aligned}(\Theta(z_{scR}) - \Theta(0))/T_* &= (T_{scR} - T_s + 0.01(z_{scR} - d - z_T))/T_* \\ &= \frac{1}{k}\left[\ln((1-y_1)/(1+y_1))\right]_{z_T}^{z_{scR}-d}\end{aligned} \qquad (3)$$

and for stable conditions

$$(\theta(z_{scr}) - \theta(0))/T_* = \frac{1}{k}\left(\ln\left(\frac{z_{scr}-d}{z_T}\right) + 5.2\,(z_{scr}-d-z_T)\right) \quad (4)$$

where

θ = potential temperature

z_{scr} = height of screen ($\simeq 1.2$ m)

T_* = $-H/\rho c_p u_*$

z_T = $0.2 z_0 \simeq 0.02 h$

h = height of foliage canopy

$d \simeq 0.63$

$k \simeq 0.4$

$$y_1 = (1 - \tfrac{16}{L}(z-d))^{1/2} \quad (5)$$

$$L = -u_*^3 T_{scr}\,\rho c_p/(kg\,(H + 0.07E)) \quad (6)$$

$\theta(0)$ may be assumed to represent the average surface temperature, with sufficient accuracy for the present purpose. The friction velocity u_* is derived using the following equations, for unstable and stable conditions respectively:

$$u(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_0}\right) - \psi_M\left(\frac{z-d}{L}\right)\right) \quad (7)$$

$$u(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_0}\right) + \frac{5.2}{L}\,(z-d-z_0)\right) \quad (8)$$

where

$$\psi_M\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+y}{2}\right) + \ln\left(\frac{1+y^2}{2}\right) - 2\tan^{-1} y + \pi/2 \quad (9)$$

and

$$y = (1 - \tfrac{16}{L}(z-d))^{1/4} \quad (10)$$

$(T_{scr} - T_s)$ cannot be determined directly from Eq (3) - (10) because L is not known. The procedure adopted used the combination formula

$$\lambda E = \frac{\Delta'(R_N - G) + \rho c_p \delta q / r_a}{\Delta' + c_p(1 + r_s/r_a)/\lambda} \quad (11)$$

and the relation

$$r_a = \frac{2.5}{u_*}\left[\ln((1-y_i)/(1+y_i))\right]_{z_T}^{z_{scr}-d} \quad (12)$$

together with the other formula, in iteration, beginning with neutral values for r_a and u_* ; the required results are obtained by successive approximation. It will be noted that R_N enters into the calculation; this is not known exactly because the calculation of part of it is the reason for the whole computation, but it may be approximated for the purpose of the iteration by

$$\left.\begin{aligned} R_N &= -70(0.1 + 0.9\,n/N) \quad \text{(night-time)} \\ R_N &= \frac{(1-\alpha_s)}{1.15} R_a (a + b\,n/N) - 60(0.1 + 0.9\,n/N) \quad \text{(daytime)} \end{aligned}\right\} \quad (13)$$

: R_N here is a flux ($W m^{-2}$)

3. Results and discussion

The calculations were carried out for the following ranges of variables:

$R_N - G$	-50 to +500 Wm^{-2}
δq	0.001 to 0.008
T_a	5 to 25 deg C
$u(10)$	2 to 10 ms^{-1}
r_s	0 to 1000 sm^{-1}
z_o	0.01 to 0.1 m

Some of these are mutually exclusive - for example: bulk stomatal resistance in the absence of recent rain will be zero only during the deposition of dew or during its evaporation early in the daytime: specific humidity deficits as large as 0.008 will occur only on occasions with relatively high air temperature, say greater than 20 deg C usually.

The calculations broke down for cases with light winds and negative available energy (radiation nights). In these meteorological conditions the surface layers are either very weakly turbulent, or turbulent only intermittently: in either case Eq (4) and (8) which apply over the range $0 < z/L < 1$ are no longer applicable. Typical least values for ΔT ($= T_s - T_{scr}$) are then around -5 deg C.

A summary of the results is presented graphically in Figure 1. This shows the following general features:-

(i) $|\Delta T|$ decreasing with increasing surface roughness

(ii) ΔT decreasing with increasing specific humidity deficit

(iii) ΔT decreasing with decreasing canopy resistance r_s

(iv) $|\Delta T|$ smaller usually at high temperatures

The calculated values for ΔT may be compared with observations obtained during three cloudless 24-hour periods by Monteith and Szeicz (1962). The average maximum net radiation for these days was around 400 hr m^{-2} and maximum values for ΔT were about 10 deg C over grass, but near zero over wheat and barley. At night ΔT decreased to about -5 deg C and -2 deg C over these short and tall crops. These results are not inconsistent with the present calculations, but exact comparison is not possible in the absence of detailed data on wind speed, vapour pressure deficit and surface roughness in Monteith and Szeicz's paper.

For practical applications it is desirable to obtain a simple expression which gives ΔT in terms of the variables, with an accuracy of say 20% or 1 deg C, whichever is the larger. The required expression can be derived entirely empirically, by trial and error, using a selection of the results produced by the computer program which solves Eq (3)-(12) but this was not attempted because of the uncertain amount of effort involved. Instead the resistance equation

$$\Delta T = \frac{H.r_a}{e c_p} \qquad (14)$$

$$\Delta T = \frac{r_a}{\rho c_p}\left[R_N - G - \frac{\Delta'(R_N-G) + \rho c_p \delta q / r_a}{\Delta' + c_p(1+r_s/r_a)/\lambda}\right] \qquad (15)$$

r_a is a function of stability which cannot be obtained directly from the input variables and so in order to obtain a useful working form of Eq(15) it is necessary to replace r_a by its neutral value

$$r_a(n) = \frac{1}{k^2 u(1.2)} \cdot \ln\left(\frac{1.2-d}{z_0}\right).\ln\left(\frac{1.2-d}{z_T}\right)$$
$$= \frac{6.25}{u(10)} \cdot \ln\left(\frac{10-6.3z_0}{z_0}\right).\ln\left(\frac{6-31z_0}{z_0}\right) \qquad (16)$$

: errors introduced by this approximated are then reduced by rewriting Eq(15) as

$$\Delta T = \frac{r_a(n)}{\rho c_p} H' f_1(H', \delta q, z_0, u) \qquad (17)$$

where

$$H' = R_N - G - \frac{\Delta'(R_N-G) + 1230\,\delta q / r_a(n)}{\Delta' + 0.41(1+r_s/r_a)\times 10^{-3}} \qquad (18)$$

A form of the function f_1 in Eq(17) which provides satisfactory values for ΔT for a wide range of variables is

$$f_1 = 1 - 0.035\,(H')^{1/4}/(u(10)/\ln(10/z_0)) \qquad (19)$$

However, although the errors which were produced by not incorporating δq in this equation are small enough to be ignored in most cases, in light winds with large values of δq the errors become unacceptably large, especially on night time occasions with negative available energy. Attempts to reduce the errors by including δq in Eq(19) were not successful. It appears likely that in order to obtain acceptable values for ΔT in all circumstances it is necessary to use iteratively equation (15) in conjunction with an expression for r_a of the form

$$r_a = r_a(n)\, f_2(H', z_0, u) \qquad (20)$$

The derivation of f_2 has not been attempted because the iterative procedure then required to obtain ΔT is probably too cumbersome for practical applications such as the calculation of net long-wave radiation for use in the estimation of potential evaporation.

Any comments or suggestions on this paper should be referred to the author.

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References

Monteith, J.L. and Szeicz, G. 1962 Radiative temperature in the heat balance of natural surfaces, Q.J.R. Met. S., 88, 496-507.

Swinbank, W.C. 1963 Long wave radiation from clear skies, Q.J.R. Met. S., 89, 339-348.

Thompson, N. 1978 Agricultural Memorandum No. 834.

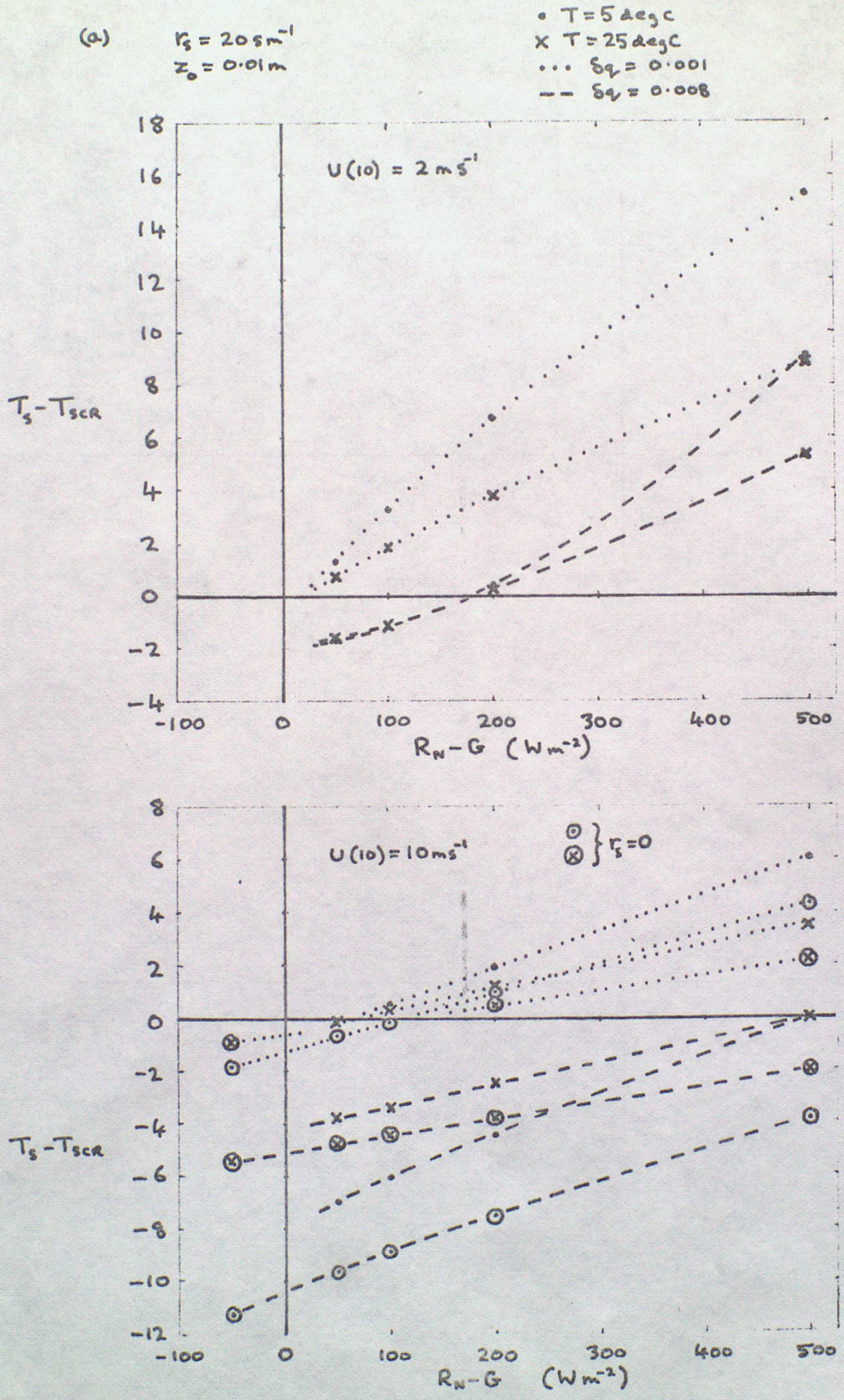
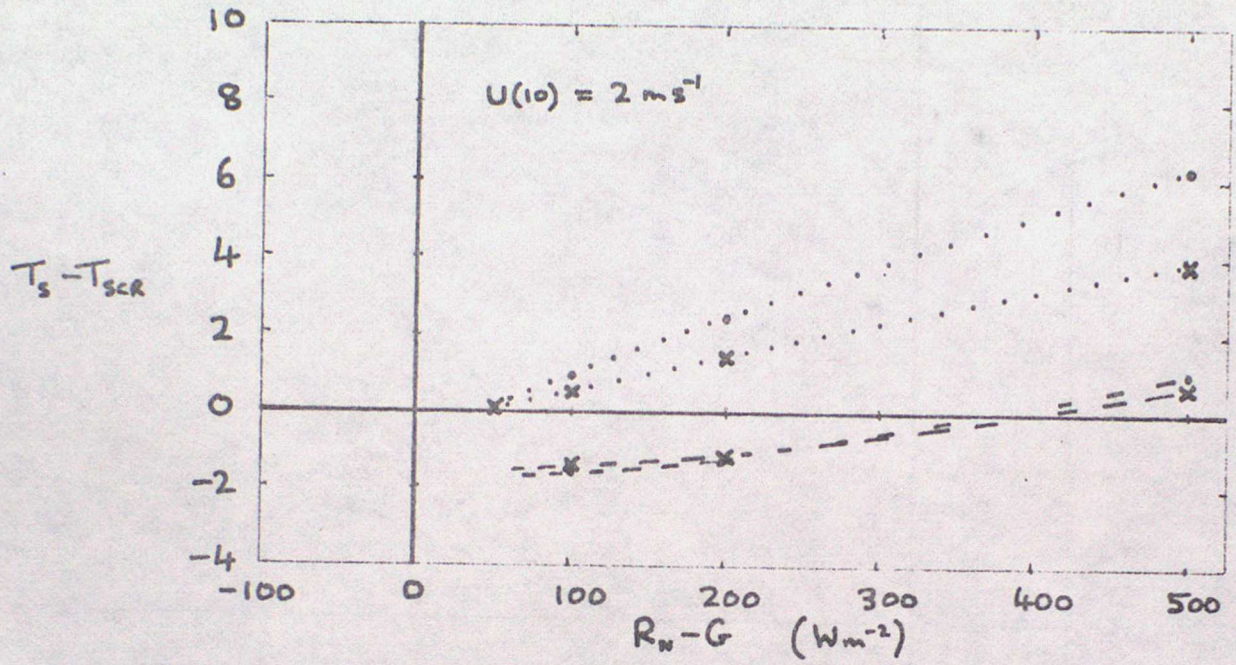


Figure 1. Differences between surface and screen temperatures

(b) $r_s = 20\ s\,m^{-1}$
$z_o = 0{\cdot}10\ m$



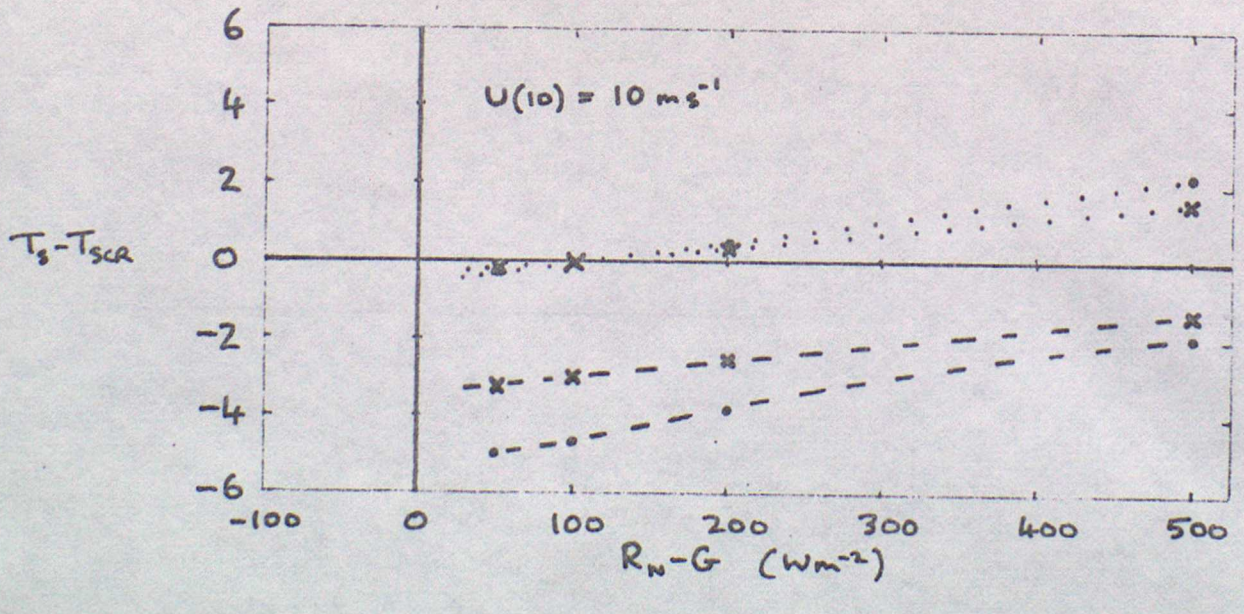


Figure 1. (continued)

(c) $r_s = 1000\ s\,m^{-1}$
$z_0 = 0.01\ m$

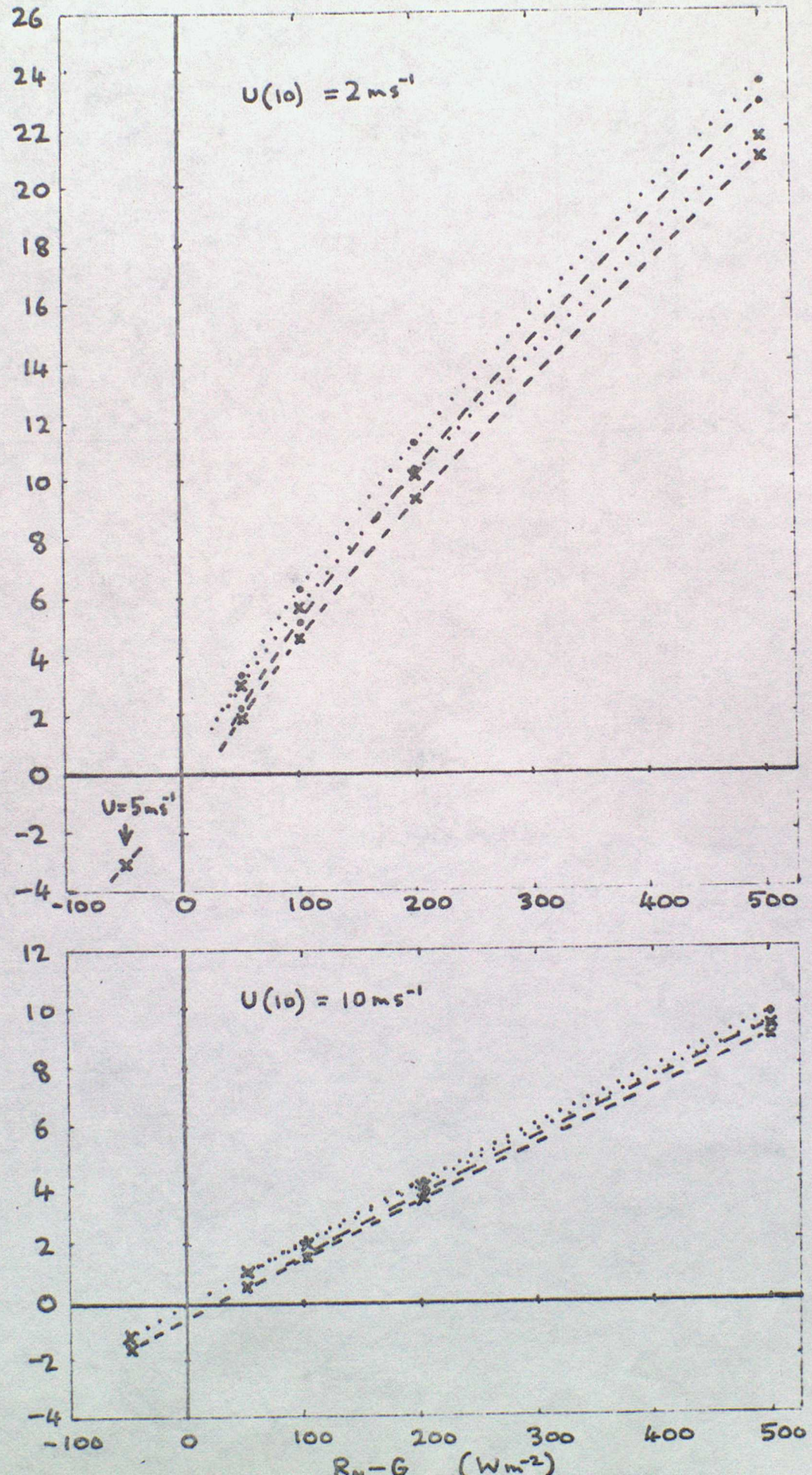
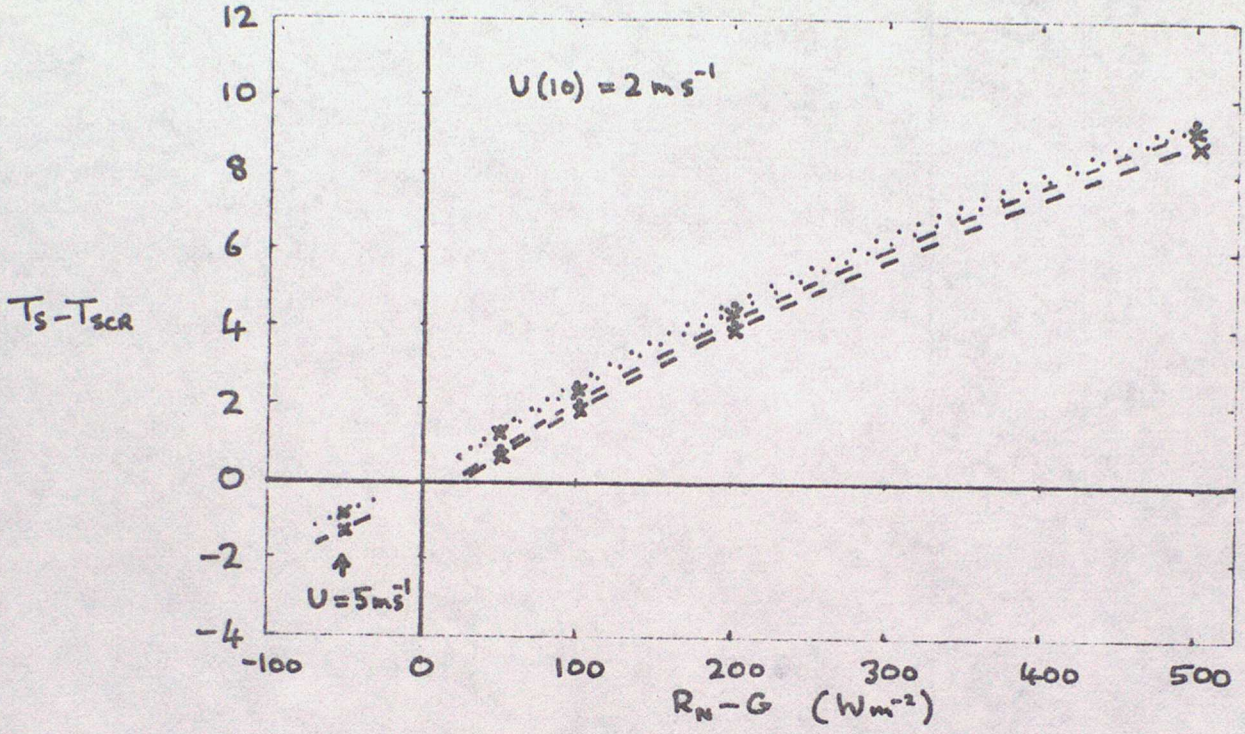


Figure 1. (Continued)

(d) $r_s = 1000\ sm^{-1}$
$z_o = 0{\cdot}10\ m$



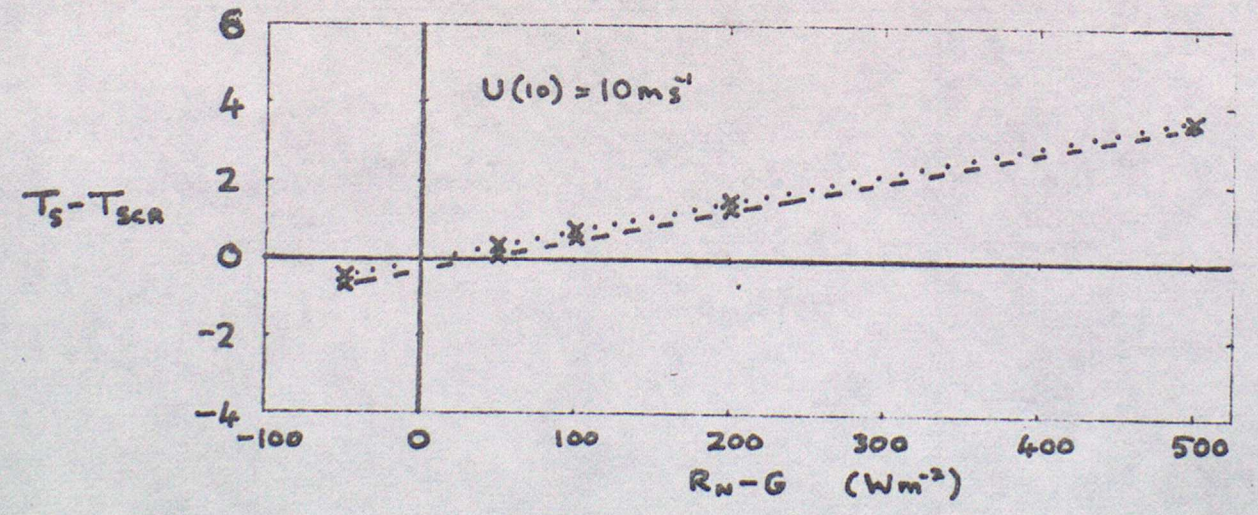


Figure 1. (Continued)